Reheating predictions in single field inflation

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- Normally when one talks about reheating, one starts by writing down couplings which leads to decay rates
- but this is difficult because 1. we don't know who the inflaton couples to and how strongly and
- 2. solving especially during preheating requires non-perturbative out of equilibrium thermal QFT, which can and have been worked on numerically but…
- It's nice, to have an easy and analytic way to make general predictions about reheating.

- instead of supposing couplings, we ignore all the microphysical details, and instead frame everything in terms of an average equation of state, w_{re}.
- gives simple way of characterizing reheating

- First start by relating inflation parameters to reheating parameters.

- starting from conservation of energy, can relate the energy density at the start of reheating to the energy density at the end:

$$0 = \nabla_\mu T^\mu_0$$

$$\int \frac{1}{\rho} d\rho = -3 \int (1+w) dN \longrightarrow \frac{\rho_{re}}{\rho_{end}} = e^{-3N_{re}(1+\langle w_{re} \rangle)}$$

$$\langle w_{re} \rangle = \frac{1}{N_{re}} \int w \, dN$$

- going to use efolding as unit of time, even though not inflating, still valid unit of time…

$$a = e^N$$

- if one picks an inflationary model, then know the energy density at the end of inflation

- can relate to the temp at the end of reheating…

$$\rho_{re} = \frac{\pi^2}{30} g_{re} T_{re}^4$$

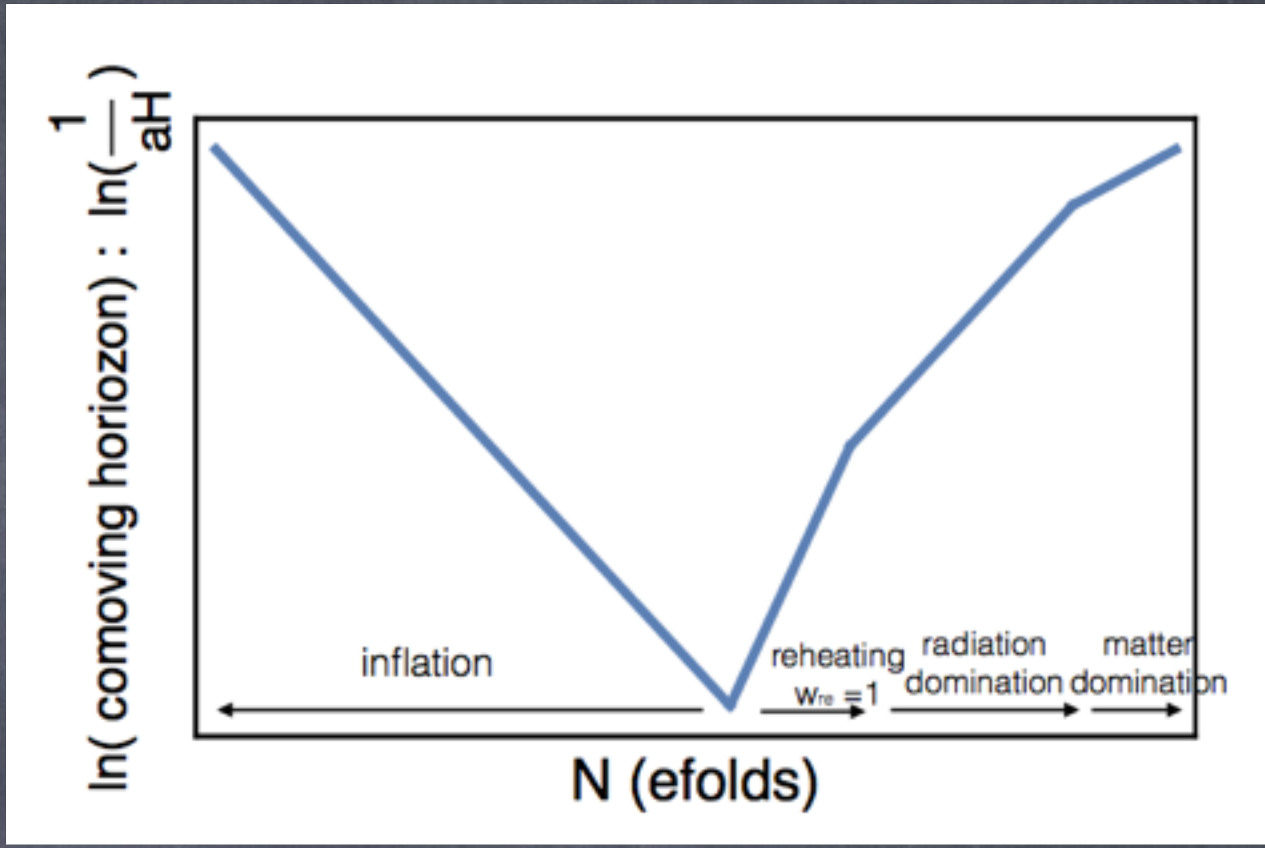
- so relating details about inflation, but to solve for N_{re} and T_{re} separately, need more information

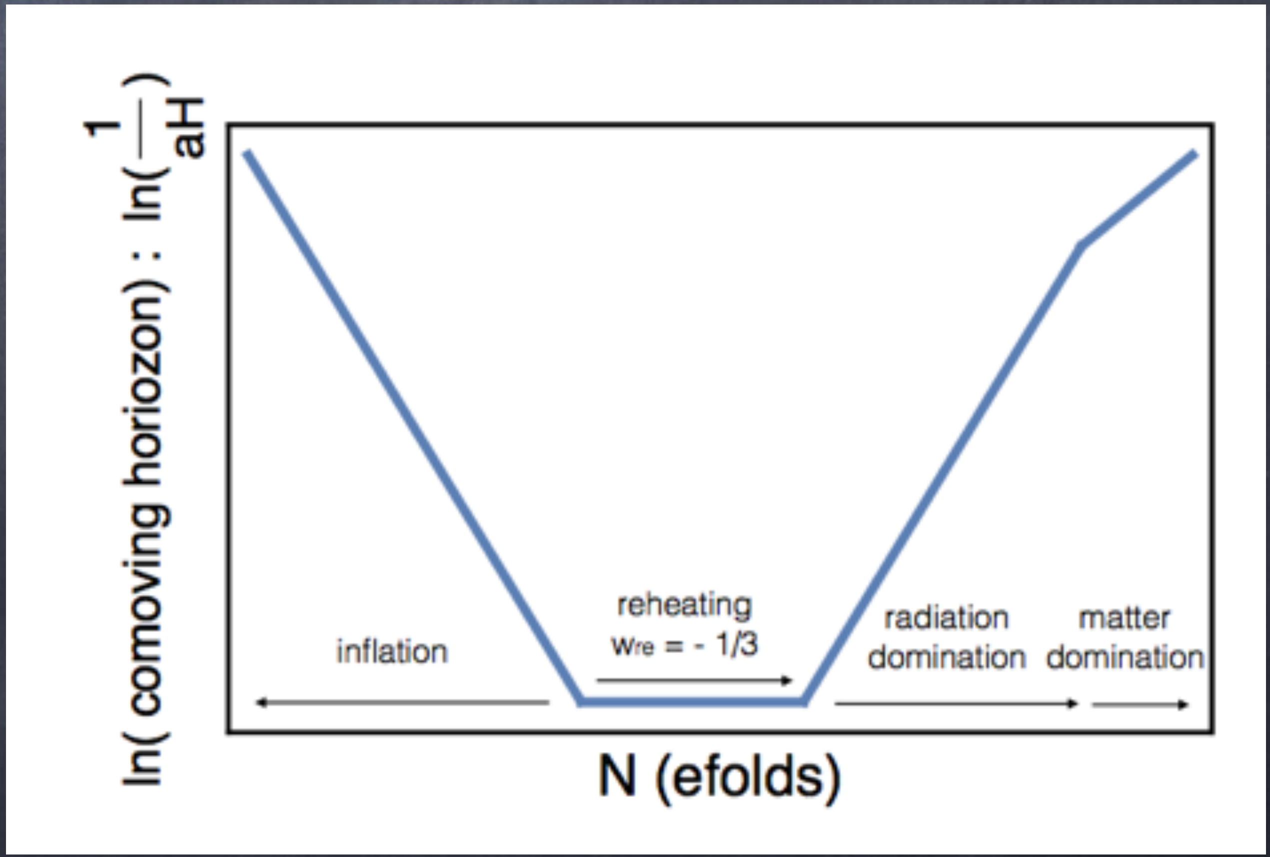
- next piece of info to relate inflation parameters to reheating is basically the solution to the horizon problem.

- aka the largest CMB modes, $l = 2$, should correspond to the size of the horizon today

- Once one chooses a model of inflation, $N_{l=2}$ can be calculated, which tells how many comoving scales left the horizon during inflation. This must = how many comoving scales must have reentered the horizon after inflation -> the horizon problem.

- what we don't know is how many modes reenter during reheating, and how many during radiation dom. Know the subsequent matter/ dark energy phase. So equation gets these 2 unknown: N_{re} and $N_{radiation}$





if $w_{re} \neq 1/3$

$$N_{re} = \frac{4}{1-3w_{re}}\left[61.6 - \ln\left(\frac{V_{end}^{\frac{1}{4}}}{H_{pivot}}\right) - N_{pivot}\right]$$

relates reheating parameter

to inflation parameters

$$T_{re} = 2.5 \times 10^{26}\, H_{pivot}\, e^{-N_{pivot}}\, e^{-N_{re}}$$

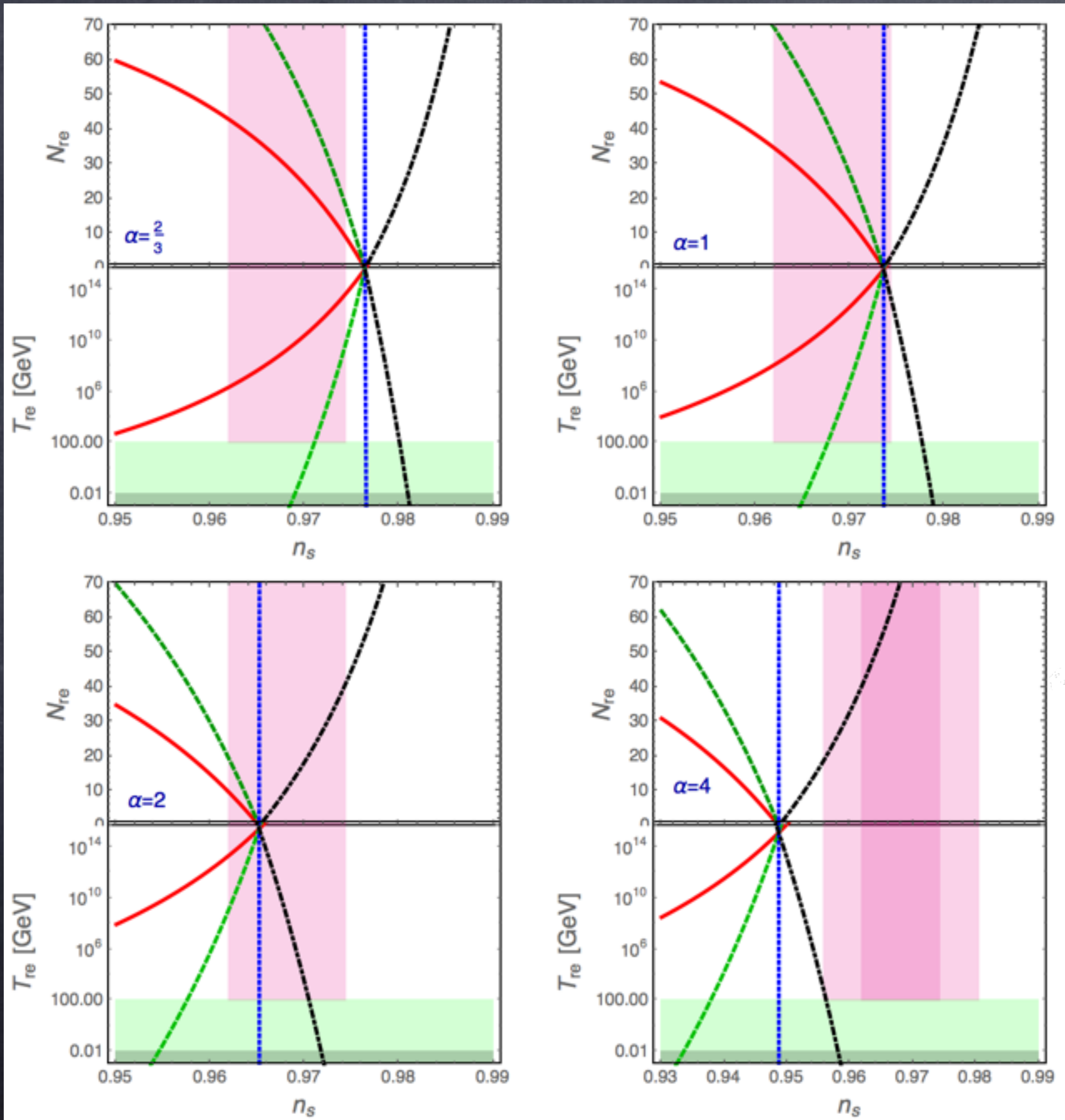
- pick a model and an equation of state, get out predictions for reheating

if $w_{re} = 1/3$

$$61.6 = \ln\left(\frac{V_{end}^{\frac{1}{4}}}{H_{pivot}}\right) + N_{pivot}$$

gives precise prediction for n_s

polynomial inflation, φ^α



$w_{re} = -1/3$

$w_{re} = 0$

$w_{re} = 1/3$

$w_{re} = 1$

Think main strength of this technique is not to constrain reheating, but to use reasonable reheating bounds to constrain inflation.

- a lot of the work using these methods has focused on $w_{re} = 0$, especially to give bounds on T_{re}.

- Think main reason for this: if you do simplest case, ignore preheating, and write inflaton equation with constant decay rate, then find the average w_{re} can come out close to 0.

Martin, Ringeval

arvix: 1004.5525

- Think if your model allows for efficient preheating phase, w_{re} near 1/3 might be more accurate.

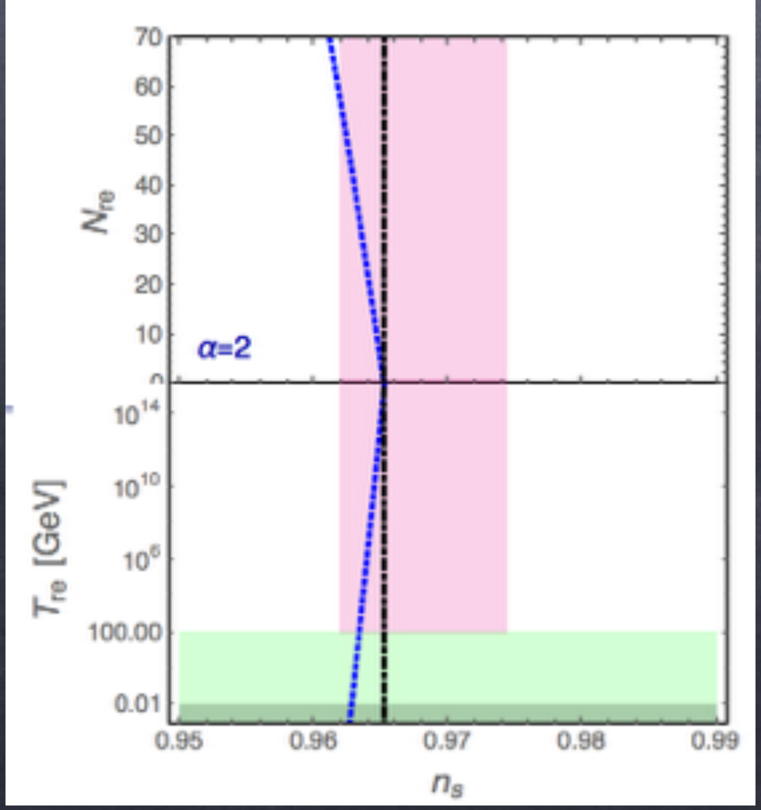
- studies that have considered inflation with short preheating phase, tend to predict w_{re} shooting up to close to 1/3 very quickly and then slowly increasing the rest of way to 1/3.

arxiv: 0507096

Podolsky, Felder, Kofman and Peloso

- then you can't really conclude anything about the temperature. But you do get a very precise prediction for n_s.

get tight predictions for n_s



$w_{re} = 0.22$

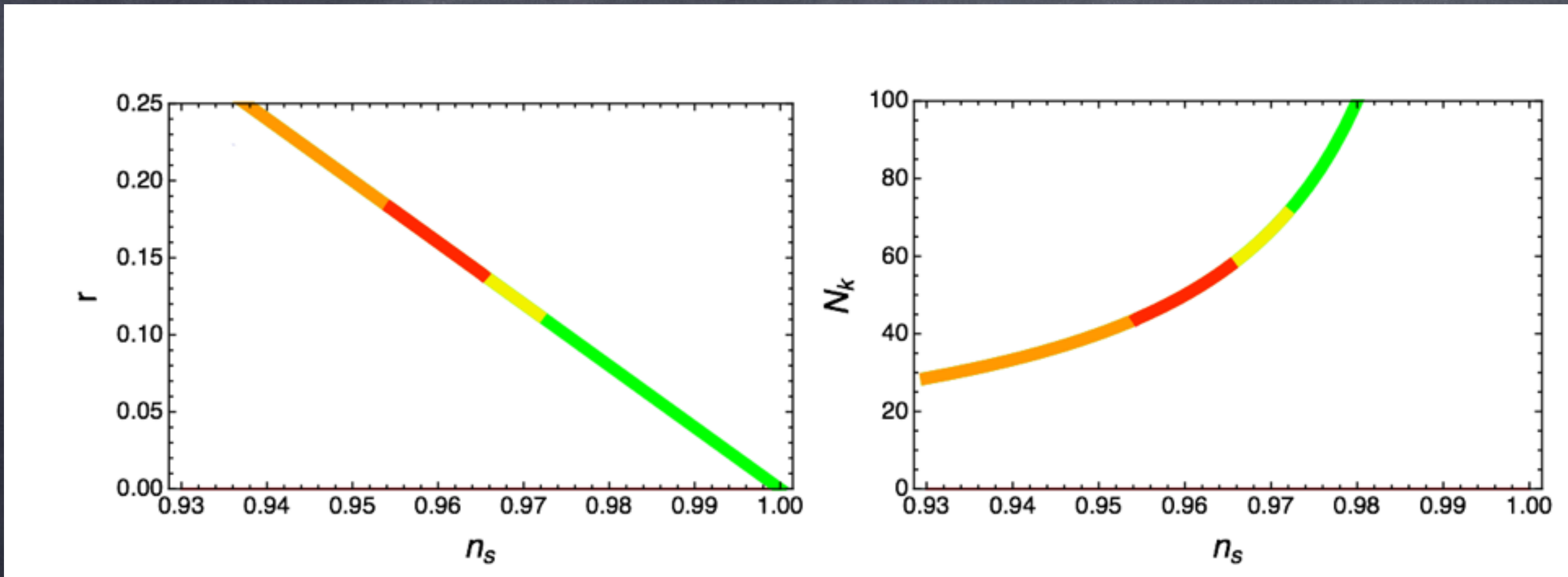
$w_{re} = 1/3$

if $w_{re} \approx 1/3$,

$n_s \approx 0.965$

φ^2

(everything evaluated at Planck's pivot, l ~ 686)



$w_{re} > 1$

$w_{re} > 1/3$

$w_{re} < 1/3$

$w_{re} < 0$

so a solution with $0 < w_{re} < 1/3$ would fall in the red region

$0.14 < r < 0.18$

$44 < N_k < 57$

$r > 0.11$

note 2 σ limit from joint BICEP/Planck analysis: $r < 0.12$

Starobinsky model

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} (R + \alpha R^2) + \mathcal{L}_{matter} \right]$$

apply a conformal transformation:

$$\tilde{g}_{\mu\nu} = (1 + 2\alpha R) g_{\mu\nu}$$

$$S = \int d^4x \sqrt{-\tilde{g}} \left[\frac{M_P^2}{2} \left[\tilde{R} - \frac{1}{4\alpha} \left(1 - e^{-\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} \right)^2 \right] - \frac{1}{2} (\tilde{\partial}\phi)^2 + e^{-2\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} \mathcal{L}_{matter} \right]$$

end up with single field model with potential

$$V = \frac{M_P^2}{8\alpha} \left(1 - e^{-\sqrt{\frac{2}{3}} \frac{\phi}{M_P}} \right)^2$$

Higgs Inflation:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R\left(1+2\xi\frac{H^\dagger H}{M_P^2}\right)+\mathcal{L}_{matter}\right]$$

same idea… apply conformal transformation…

$$\tilde{g}_{\mu\nu} = \left(1+2\xi\frac{H^\dagger H}{M_P^2}\right)g_{\mu\nu}$$

then rewrite in terms of new canonically normalizable field, and using a few approximations…

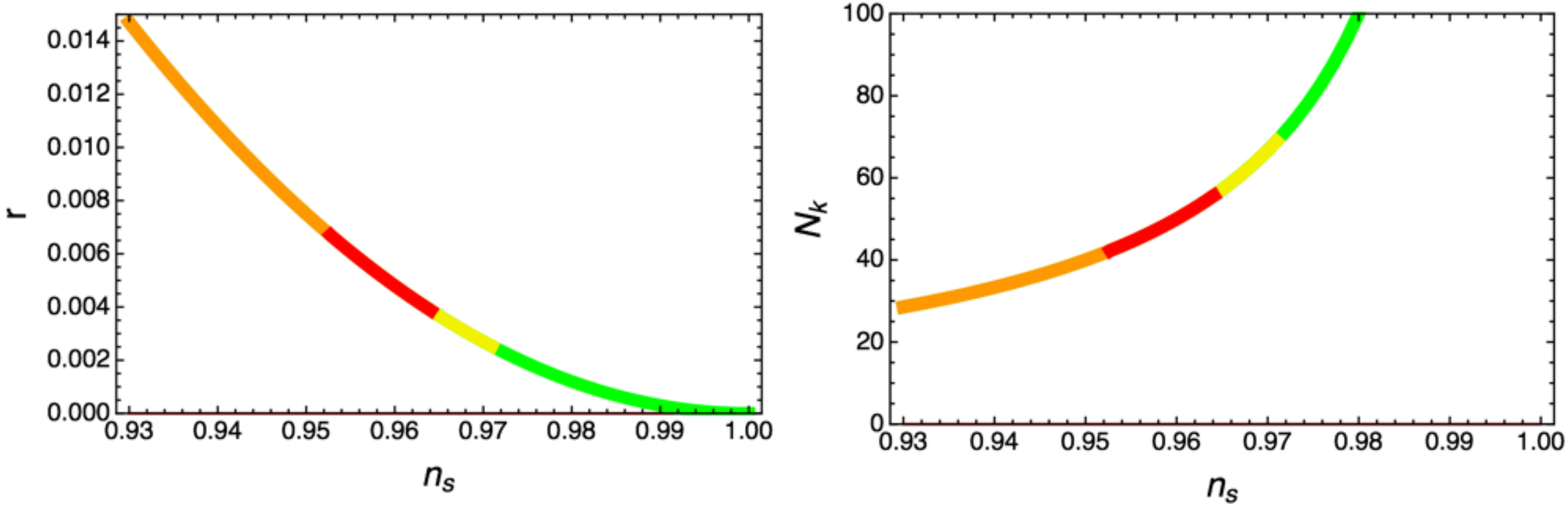
end up with a canonically normalized field $\bar{h}$ (function of the SM higgs) evolving under a potential:

$$V = \frac{\lambda M_p^4}{4\xi^2}\left(1-e^{-\sqrt{\frac{2}{3}}\frac{\bar{h}}{M_P}}\right)^2$$

same potential as the R^2 case

- Said take approximations… potential not the same at low scales, but it same at inflation scales. So expect if one modeled exact reheating dynamics, would get different behavior.
- But said reheating predictions assuming constant equation of state just depends on inflation predictions…
- so since at inflation scales have same potential, find same predictions for reheating parameter space when parametrized in terms of an average equation of state).
- Idea is, the allowed parameter space as a function of w_{re} is the same, but the most likely w_{re} for each model is likely different.

Starobinsky/ Higgs inflation model



$w_{re} > 1$

$w_{re} > 1/3$

$w_{re} < 1/3$

$w_{re} < 0$

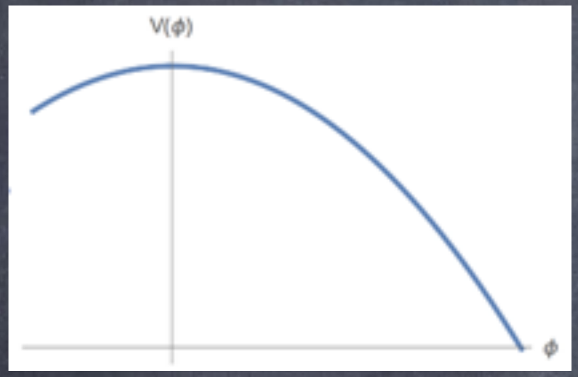
and solution with $0 < w_{re} < 1/3$
would fall in the red region

$0.953 < n_s < 0.964$
$0.004 < r < 0.007$
$42 < N_k < 56$

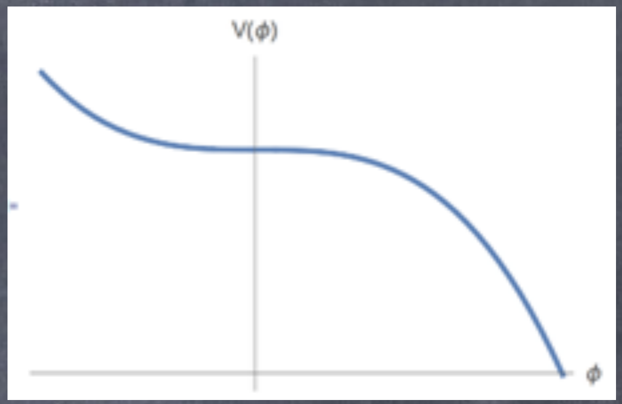
- Also considered hilltop model...

$$V = M^4 \left[1 - \left(\frac{\phi}{\mu}\right)^p\right]$$

if p even, looks like:

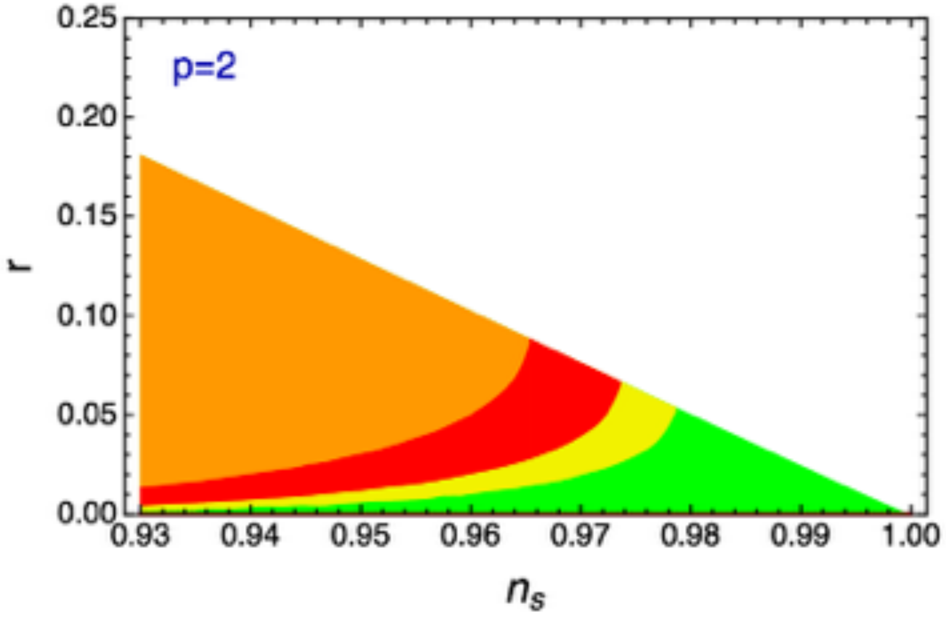


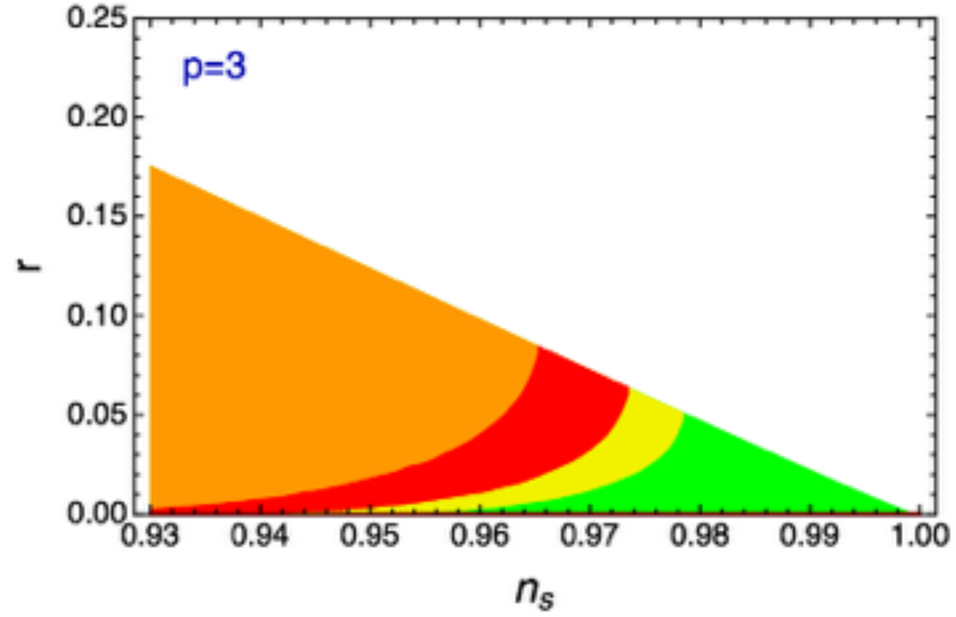
if p odd, looks like:



so potential starts very flat, gets steeper

note 2 free parameters now, will draw out shape instead of line in n_s vs. r plane





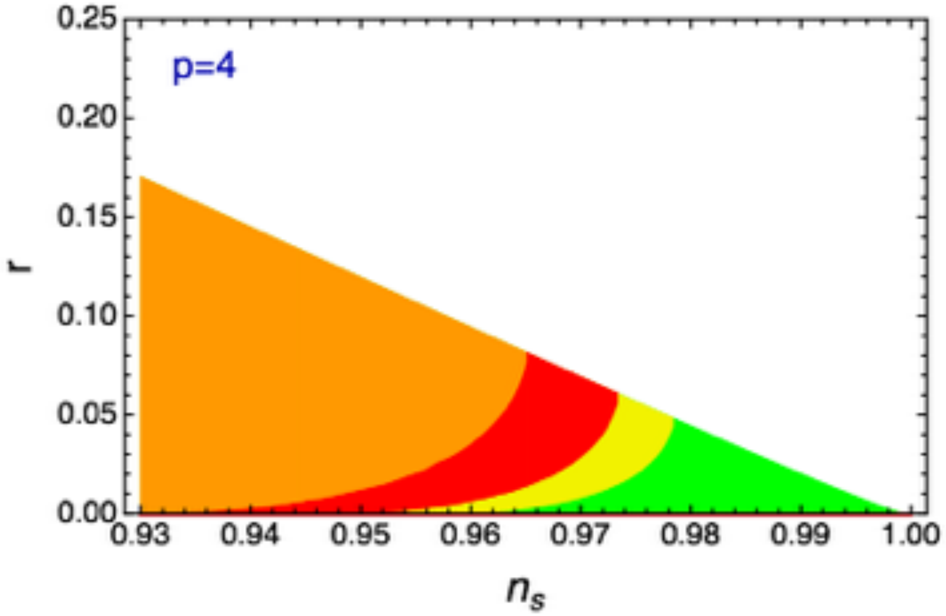
$$V = M^4 \left[1 - \left(\frac{\phi}{\mu} \right)^p \right]$$

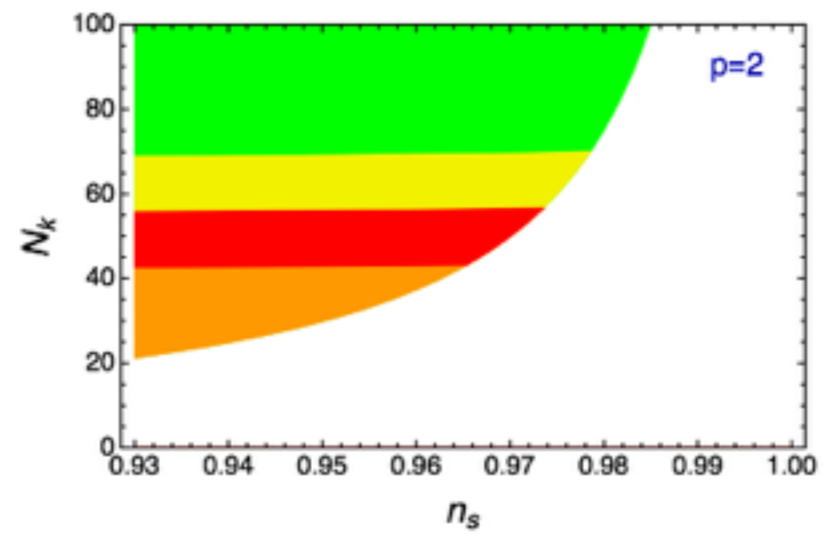
$w_{re} > 1$

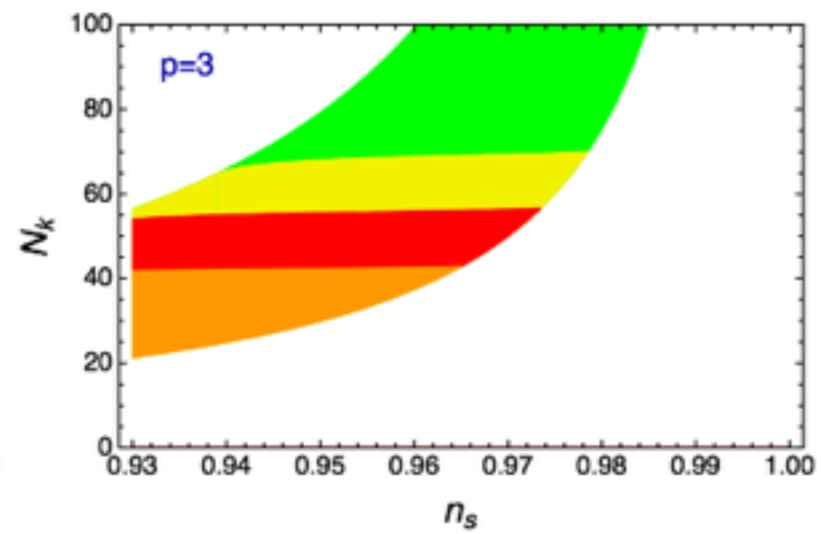
$w_{re} > 1/3$

$w_{re} < 1/3$

$w_{re} < 0$







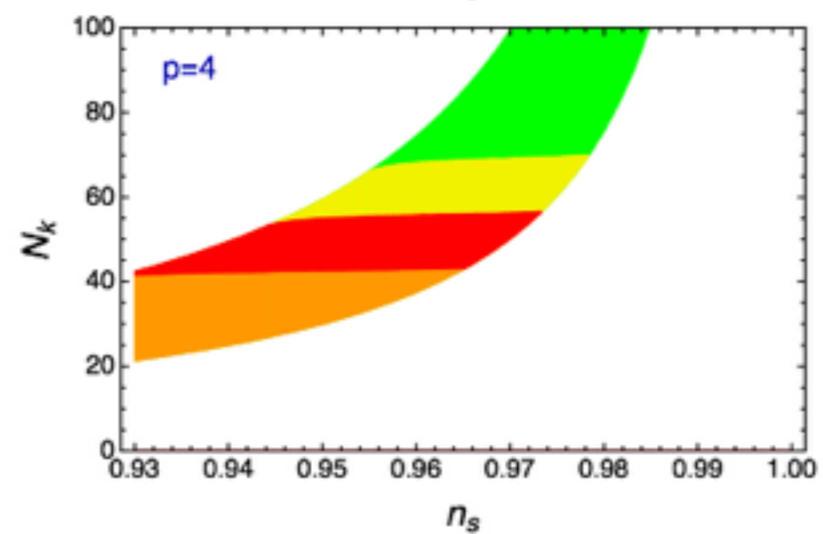
using Planck's 2 σ bounds on n_s:

$w_{re} < 1/3$ gives:

p= 2 r > 0.02

p=3 r > 0.007

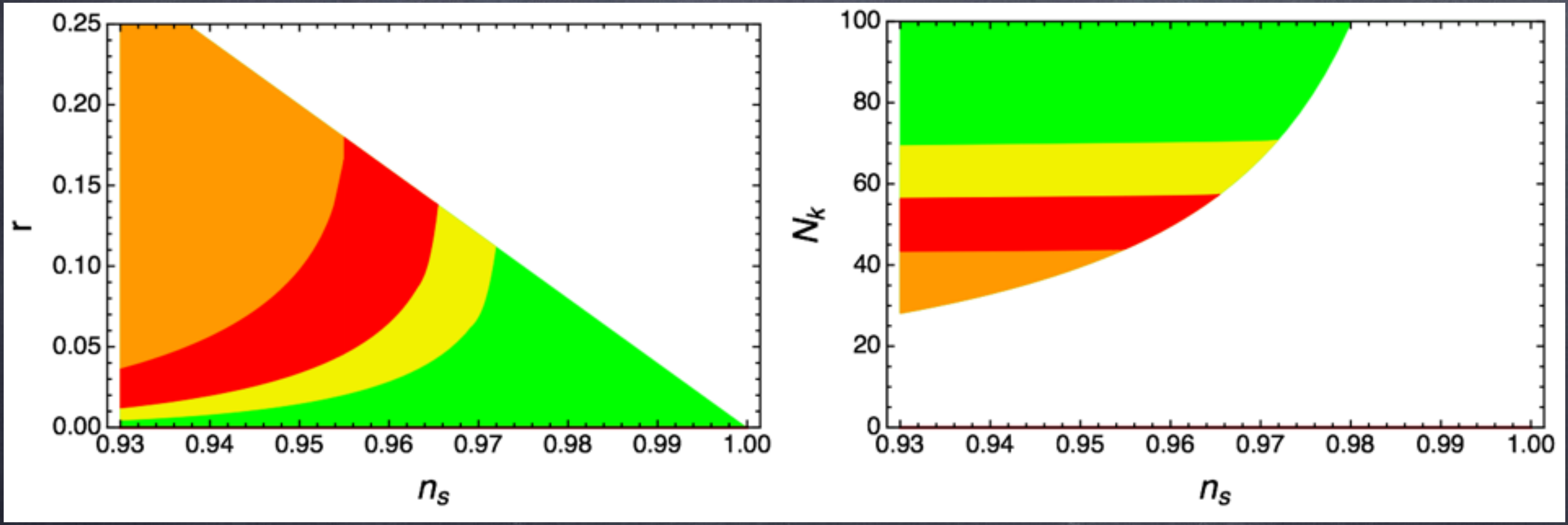
p=4 r > 0.003



natural inflation

$$V = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

again have 2 free parameters



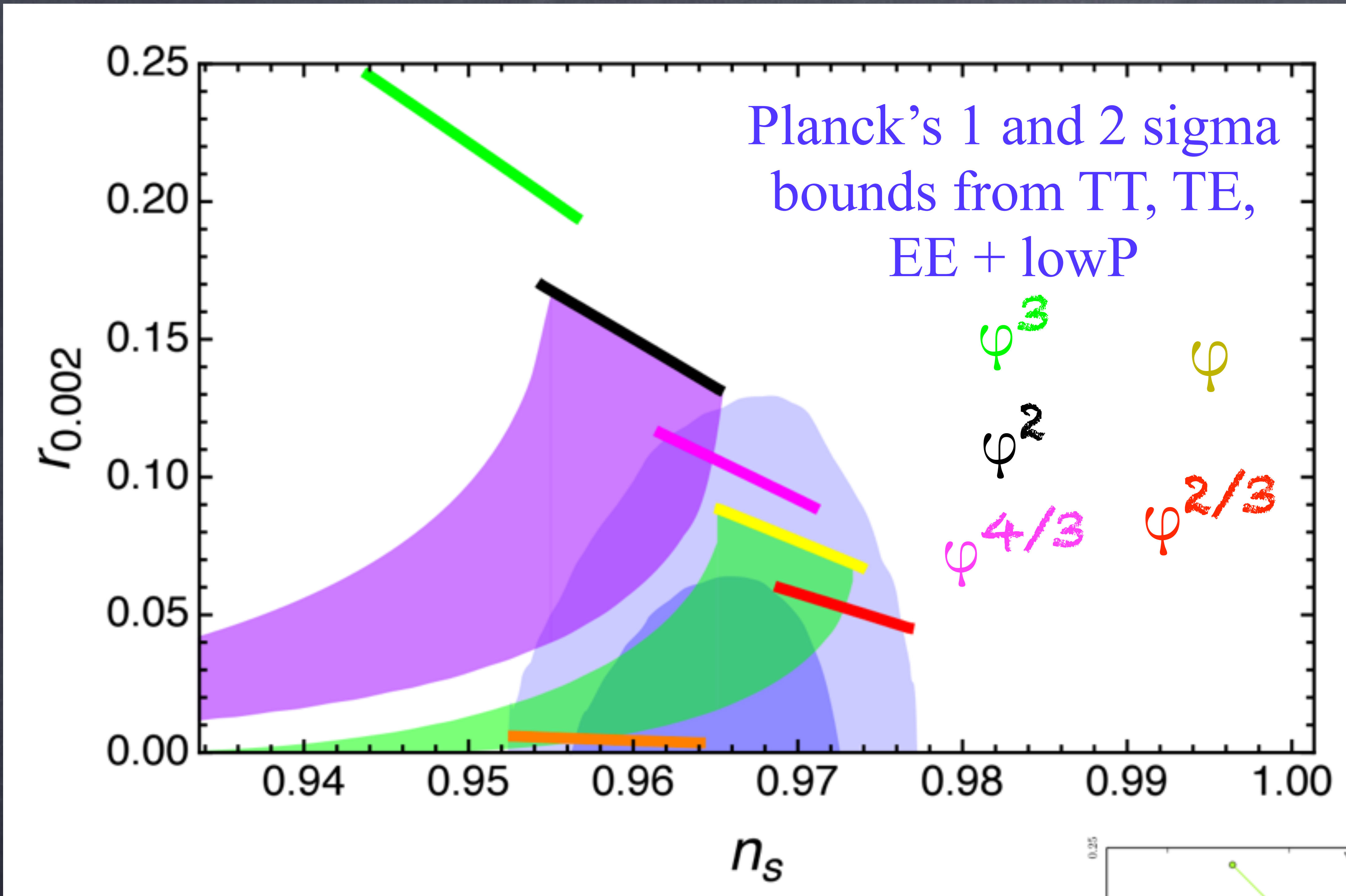
$w_{re} > 1$

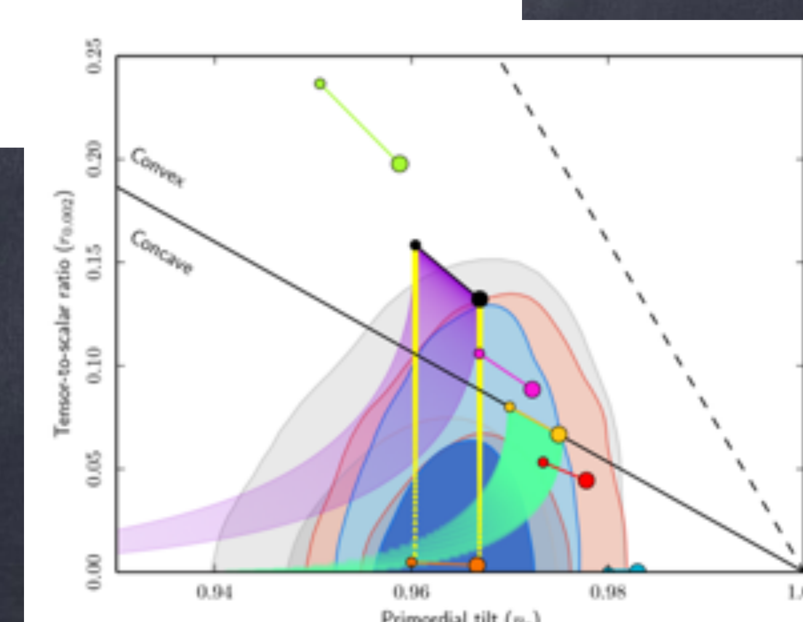
$w_{re} > 1/3$

$w_{re} < 1/3$

$w_{re} < 0$

$w_{re} < 1/3$ gives $r > 0.05$
and favors $n_s <$ Planck's central value





R^2

natural

quartic hilltop